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CRYOGENIC RECOVERY

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ABSTRACT

Because of the low boiling temperature of cryogenic propellants to be used on the Space Shuttle, loss of cryogens from boil-off could become very costly. This paper describes how this shuttle problem is being solved at Kennedy Space Center. Cryogenic losses are categorized relative to the particular cryogenic involved, the Space Shuttle servicing operation causing boil-off and the magnitude of the loss. The techniques under consideration are discussed in detail. These techniques include reclaiming the boil-off by reliquefaction, upgrading the reclaimed boil-off by purification, and interim boil-off storage in metal hydride prior to reprocessing. One of the reliquefaction processes discussed in detail utilizes the cooling effect of venting some of the liquid hydrogen boiloff to provide a simple hydrogen reliquefaction unit.

Possible future applications of these cryogenics recovery techniques to industry and transportation systems using liquid hydrogen for energy storage and fuel are also discussed.

INTRODUCTION

The Space Shuttle Main Propulsion System will be fueled with approximately 221,429 pounds (100,438 kilograms) or approximately 374,436 gallons (1417.39 cubic meters) of liquid hydrogen (LH2). This system will also be fueled with 1,329,571 pounds (603,083 kilograms) or approximately 133,605 gallons (528.46 cubic meters) of liquid oxygen (LOX).

At Kennedy Space Center, LH2 will be stored in two vacuum and perlite insulated spherical storage tanks, each holding 850,000 gallons (3217.60 cubic meters). The LOX will be stored in two perlite insulated 900,000 gallon (3406.87 cubic meters) spherical storage tanks.

As part of an on-going investigation to improve the state-of-the-art in storage and distribution of large quantities of cryogenic propellants, the recovery of cryogenics boiloff appears to be cost effective.

The cryogenic recovery methods being considered at Kennedy Space Center are presented in this paper.

Space Shuttle Servicing Operations causing Cryogenic Boiloff

Between Space Shuttle launches, LH2 and LOX will be stored in storage tanks at launch complexes 39A and B. During this storage period, the storage tanks will be replenished by over-the-road trailer transporters.

When the Space Shuttle is fueled, approximately 1600 feet (487.68 meters) of transfer piping between the storage sphere and the shuttle will be chilled down. LH2 transfer from the storage sphere to the shuttle will be accomplished by applying approximately 65 psig (448,159 N/M2 or newton per square meter) gas pressure to the liquid in the storage sphere by vaporizing LH2 and flowing the gas vapor back to the storage sphere. During LH2 loading operations, heat transfer into the Space Shuttle External Tank will cause rapid boiloff which will be piped away from the vehicle for safe disposal because of its flammability.

LOX will be pumped to the Space Shuttle. The LOX storage vessel will be pressurized to approximately 10 psig (68.975 N/M2) to prevent the pressure of LOX at the pump suction from falling below the required pump suction pressure. LOX boiloff losses occur during storage, storage tank replenish, system chilldown, and Space Shuttle loading similar to LH2 boil-off losses.

After the shuttle is launched, the pressurized gas in the storage tanks will be vented for system safin.

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Magnitude of Cryogenic Boiloff

To estimate the magnitude of cryogenic boiloff, total Space Shuttle Program losses from Kennedy Space Center, Florida and Vandenberg Air Force Base, California for a total of 572 launches from 1978 through 1991 was considered. Estimated cryogenic boiloff losses during this time period are as follows:

(1) Boiloff of LH₂ during storage:
5,073,300 pounds (2,301,210 kilograms) or
8,578,950 gallons (32,474.86 cubic meters).

(2) Rapid LH₂ boiloff during loading:
50,353,000 pounds (22,839,738 kilograms) or
85,149,823 gallons (322,316 cubic meters).

(3) LH₂ tank depressurization after launch:
4,882,000 pounds (2,205,360 kilograms) or
8,221,642 gallons (31,122 cubic meters).

(4) LOX boiloff during storage:
181,448,800 pounds (82,303,796 kilograms) or
19,052,124 gallons (72,120 cubic meters)

This totals over one hundred million gallons (378,541 cubic meters) of liquid hydrogen.

Techniques Being Considered to Recover Cryogenic Boiloff

Techniques being considered to recover cryogenic boiloff are as follows:

(1) Boiloff of LH₂ during storage

All or part of this boiloff can be recovered by reliquefaction. It is more economical to reduce the temperature of the boiloff gas a few degrees than to procure new LH₂ from the manufacturer. The conventional system for re liquefaction of hydrogen uses hydrogen/hydrogen, liquid nitrogen/hydrogen and freon/hydrogen heat exchangers.

This type of system is being compared with a simpler system using only one hydrogen/hydrogen heat exchanger. The simpler system uses the refrigeration effect of venting some of the boiloff gases to eliminate the requirement for freon and liquid nitrogen cooling downstream of the compressor. In this system, boiloff gas passes through the shell side of a hydrogen/hydrogen heat exchanger. At the exchanger exit, approximately 20 percent of the boiloff will be vented through a thermal control valve to cool the hydrogen prior to entering the compressor. The compressor raises the pressure of the gas to 600 psig (4,136,854 N/M²) raising the gas temperature to approximately 140° Rankine (78° Kelvin). The gas is then passed back through the tube side of the same hydrogen/hydrogen heat exchanger to lower the temperature to approximately 60° Rankine (33° Kelvin). The gas is then expanded by pressure control through a Joule-Thomson expansion valve back into the storage tank where approximately 66 percent of the initial gas enters the tank as liquid and the remainder mixes with new boiloff and repeats the cycle. The advantage to the simple system is possible lower installation, operational and maintenance costs.

Reliquefaction cycles using liquid nitrogen cooling with both open and closed cycles are being evaluated. The open cycle passes the reliquefied hydrogen back into the storage tank and the closed cycle uses a heat exchanger in the tank and the refrigerated LH₂ condenses hydrogen gas inside of the tank without passing the fuel through the refrigeration cycle. The closed loop cycle has the disadvantage of reduced efficiency by utilizing another heat exchanger, but it has the advantage of preventing possible contamination of the LH₂ and providing a system that can operate independent of LH₂ system operation.

Each of these reliquefaction techniques are being studied to determine the optimum technique, thermodynamic cycle, capacity, component sizing, control system, LH₂ tank interface configuration, reliquefaction system location, safety monitoring and fire prevention.

(2) Rapid LH₂ Boiloff during Loading

During system chilldown, and LH₂ loading rapid boiloff occurs. During loading of Saturn V and uprated Saturn I launch vehicles, rapid LH₂ boiloff was piped from the vehicle to a hydrogen burn pond for safe disposal away from the vehicle. Several options are being evaluated relative to recovery of this hydrogen. These options include chemically storing the hydrogen gas in a metal hydride, compressing the gas and/or reliquefying the gas as it is piped from the Space Shuttle. Metal hydrides offer a chemical means for storing hydrogen at high densities without high pressures or low temperatures. For example, the storage of hydrogen as titanium hydride achieves a storage density of 1.2 times that possible for liquid storage.

Metal hydride recovery and storage of rapid hydrogen boiloff losses is more advantageous than direct compression or reliquefaction because the systems required to process the gas at the high boiloff rate would be large and costly. Storage of the rapid boiloff using metal hydride would require a large container of hy-
dride and cooling water to cool the hy-
dride as gas enters.

After launch, hydrogen can be removed from
the hydride by heating and liquefied or
compressed as required.

(3) LH2 Tank Depressurization after Launch

Recovery of hydrogen gas vented from the
LH2 storage tank after launch will prob­
ably require a reliquefaction system
using liquid nitrogen refrigeration. The
requirement to replenish the storage tank
between launches may not allow sufficient
time to reliquify enough hydrogen to re­
duce the tank pressure so LH2 can be
flowed into the tank. In addition, this
reliquefaction process may require an
isentropic expander in lieu of a Joule-
Thomson expansion valve if liquid nitro­
gen cooling is not used, and the reli­
ability of isentropic expanders at the
low temperature required is questionable.
The reliquefaction system that can handle
both this case and daily boiloff are being
evaluated simultaneously.

(4) LOX Boiloff during Storage

Reliquefaction of LOX boiloff during stor­
age is being evaluated. It may be possi­
bile to purify the LOX during reliquefac­
tion to a fuel cell grade. Some of the
typical methods of reliquefaction being
considered evolve the following tech­
niques:

- Gas boiloff to compressor to
  expander to LOX.
- Gas boiloff to purifier to refri­
gerator to LOX.
- Gas boiloff to LH2 condenser to
  LOX.

It may be possible to use the same reli­
quefaction system on both LH2 and LOX fill
manifold chilldown boiloff gas generated
when the storage tanks are being replen­
ish. Recovery of rapid LOX boiloff
losses from the Space Shuttle was not
considered because this boiloff is vented
directly to the atmosphere. Connection
of LOX boiloff flyaway vent piping to the
shuttle would be very costly and failure
to function properly may jeopardize the
launch mission.

INDUSTRIAL APPLICATION

Industrial application of cryogenic re-
covery at cryogenic production plants is
already in process. Use of reliquefaction
systems will be cost effective at major
airports when LH2 is adopted as a prime
fuel. (3)

Metal hydrides are being considered for

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If depletion and/or scarcity of fossil
fuels causes LH2 to become a prime energy
storage media, the recovery of cryogens
will be an asset to energy conservation.
It is possible that some of the cryogenic
recovery effort at Kennedy Space Center
could have future applications to industry.